PROBING THE DEPTHS OF SPACE WEATHERING: A CROSS-SECTIONAL VIEW OF LUNAR ROCK 76015. S. K. Noble[1], L. P. Keller[1] and R. M. Stroud[2], [1]NASA Johnson Space Center, Mail Code KR, Houston TX 77058, Sarah.K.Noble@nasa.gov. [2]Naval Research Laboratory, Code 6360, Washington, DC 20375.

Introduction: The term "space weathering" refers to the cumulative effects of several processes operating at the surface of any solar system body not protected by a thick atmosphere. These processes include cosmic and solar ray irradiation, solar wind implantation and sputtering, as well as melting and vaporization due to micrometeorite bombardment [1].

Space weathering discussions have generally centered around soils but exposed rocks will also incur the effects of weathering. Rocks have much longer surface lifetimes than an individual soil grain and thus record a longer history of exposure. By studying the weathering products which have built up on a rock surface, we can gain a deeper perspective on the weathering process and better assess the relative importance of various weathering components.

The weathered coating, or patina, of the lunar rock 76015 has been previously studied using SEM and TEM [2,3,4]. It is a noritic breccia [5] with both "glazed" (smooth glassy) and "classic" (microcratered and pancake-bearing) patina coatings [2]. Previous TEM work on 76015 relied on ultramicrotomy to prepare cross sections of the patina coating, but these sections were limited by the "chatter" and loss of material in these brittle samples. Here we have used a focused ion beam (FIB) instrument to prepare cross sections in which the delicate stratigraphy of the patina coating is beautifully preserved.

Methods: After thoroughly examining the sample in a conventional SEM, interesting regions were selected for TEM analysis. Using a FEI Nova 600 FIB-SEM instrument with an in situ micromanipulator at the Naval Research Lab, a cross section (roughly 6 μm wide by 4 μm deep) of the weathered patina was removed and prepared for TEM analysis.

TEM work was done using the recently installed JEOL 2500SE 200 keV field-emission scanning-transmission electron microscope (FE-STEM) at JSC. The FE-STEM is equipped with a large-area, thin window energy-dispersive X-ray (EDX) spectrometer. Spectrum images of the sample were acquired with a 2 or 4 nm incident probe whose dwell time was minimized to avoid beam damage and element diffusion during mapping. Successive image layers of each mapped region were acquired and combined in order to achieve suitable counting statistics for major elements (e.g. Mg, Al, Si, Ca, Ti, and Fe) in each pixel.

Results and Discussion: The FIB sample reveals a complex layer of weathered material deposited on a largely plagioclase substrate (Fig 1). The weathering patina ranges in thickness across our sample from ~100 nm to over 1.5 μm, though previous studies of 76015 [2,3] suggest that the patina is highly variable, ranging in thickness from nothing to an estimated 20 μm in regions. The underlying plagioclase grain in the section is particle track-rich with a thick (~100 nm) amorphous irradiated rim (light pink in Fig 1). This irradiated rim is identical in composition to the parent grain (Fig 2). Immediately above the irradiated rim are several fine layers of $npFe^0$-bearing amorphous silicate material (Fig 3). Similar layering is common in soil rims and is the result of vapor or sputter deposited material [6]. Overlying these thin layers, there is a thick (50-150 nm) $npFe^0$-bearing layer that extends across the entire section. The element maps in Fig 2 show that this layer is enriched in Fe, Ti, and Si. The thickness and higher Ti content of this layer suggests an origin as a melt splat rather than vapor or sputter deposition. Above this distinctive layer, there are many glass layers and "splats" of varying size, some stretching across much of the section, others only a few hundred nanometers in extent. EDX mapping reveals much compositional heterogeneity among these glass units. The boundaries between units are generally sharp, suggesting fast cooling rates. Some are rich in $npFe^0$, others have little or none. The $npFe^0$ ranges in size from ~1 to 50 nm in diameter, though the vast majority is under 10 nm, similar to sizes seen in soil rims rather than the larger blebs more commonly found in agglutinates. In general, it appears that the smaller units often are the most enriched in $npFe^0$ while the larger units typically have less. Several small plagioclase grains (and a single glass clast) have been entrained amongst the glass units (Fig 1). Most of these grains are also track-rich, with track-densities on the order of $\sim 1 \times 10^{11}$ cm^{-2}, similar to what was seen by [4]. Two of the entrained grains were found to have their own irradiated rims. $NpFe^0$ is also concentrated around some of these accreted grains, particularly the glass clast and the largest plagioclase clast. Presumably, this material represents weathered rims acquired by these grains before their accretion on to the rock surface.

The literally dozens of layers and units of weathering products seen in this one small sample illustrates the complex and stochastic nature of space weathering. Future samples will allow us to generalize better about the variability and variety of weathering products produced on the lunar surface.

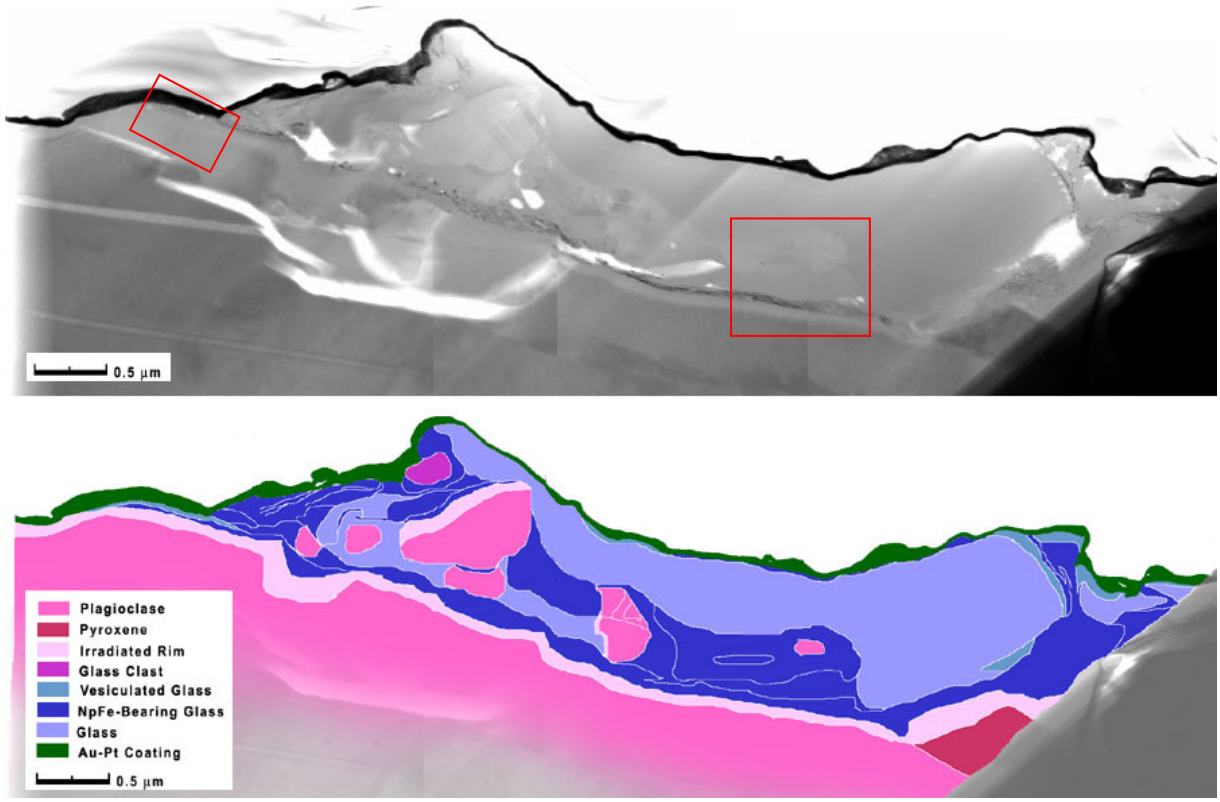


Figure 1. FIB cross section of the weathered coating on lunar breccia 76015. Red boxes show location of Figs 2 and 3.

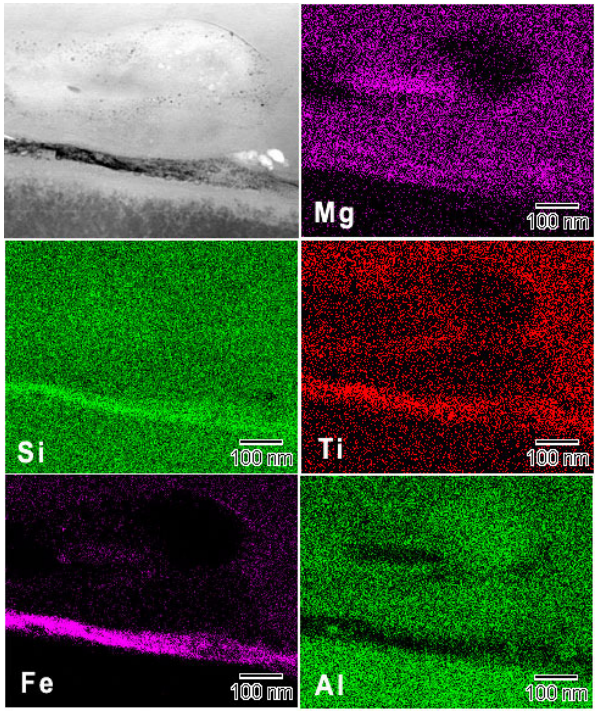


Figure 2. Element maps of a small region from the FIB samples showing the plagioclase grain with several layers of glass, some of which are nanophase Fe^0-rich. There is also a small entrained plagioclase grain in the upper right.

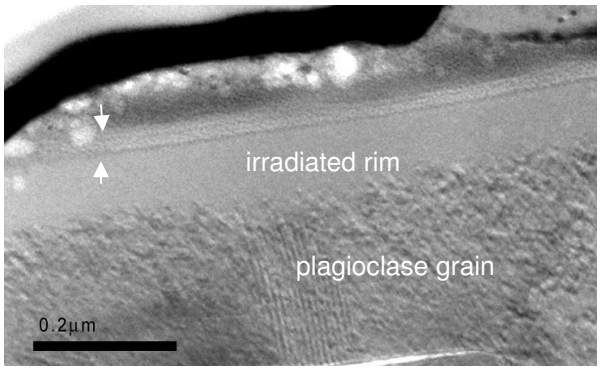


Figure 3. Several very fine scale layers can be seen in the nanophase Fe^0-rich glass above the irradiated zone in this TEM bright field image.

References: [1] Hapke B. (2001) *JGR,* 106, 10039-10073. [2] Wentworh S.J. et al. (1999) *MaPS, 34,* 593-603. [3] Keller L.P. and McKay D.S. (1997) *GCA*, 61, 2331-2341. [4] Keller L.P. et al. (1996) 27th *LPSC*, 661. [5] Rhodes J.M. et al. (1974) 5th *PLPSC,* 1097-1117. [6] Blanford G.E. et al. (1974) 5th *PLPSC,* 2501-2526.

Acknowledgements: Grants from the NASA SRLIDAP program supported the purchase of the JEOL 2500SE STEM and development of FIB preparation techniques. This work is supported in part by a grant from the NASA Cosmochemistry program (LPK). Support of ORAU through the NASA Postdoctoral Program to SKN is greatly appreciated.

Probing the Depths of Space Weathering: A Cross-Sectional View of Lunar Rock 76015

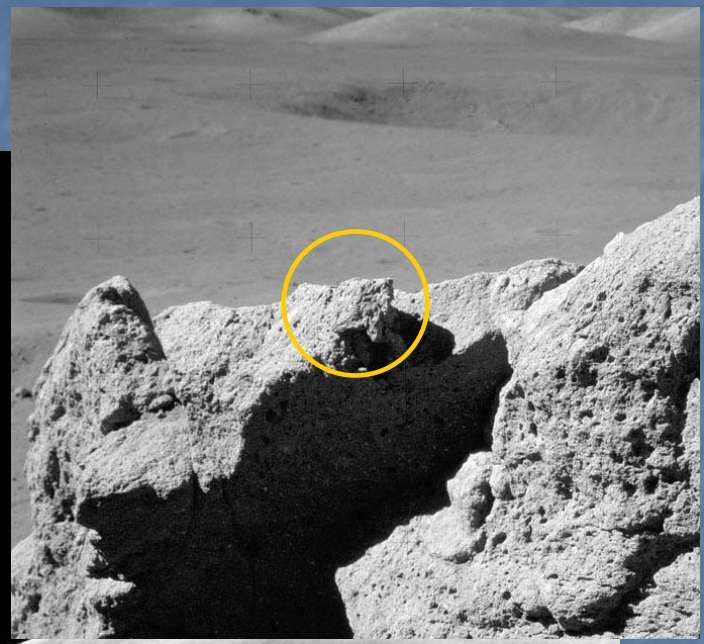
Sarah Noble
Lindsay Keller
NASA JSC

Rhonda Stroud
Naval Research Lab

Nick Teslich
Lawrence Livermore National Lab

76015

Noritic melt breccia from “split rock” at Station 6

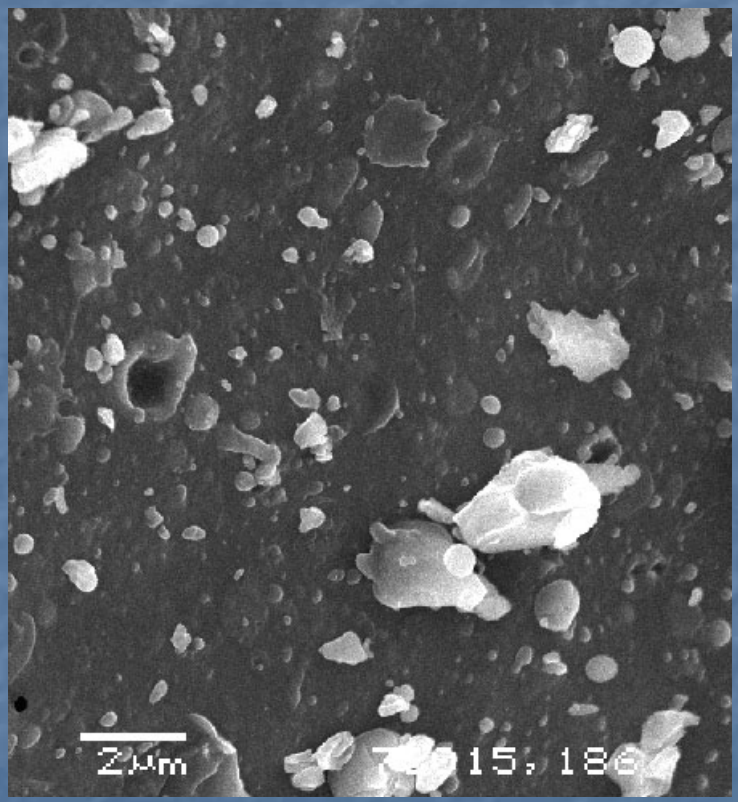


Weathering of Rocks vs. Soils

- This rock has been in place for a very long time (~22 Ma)
- “Witness plate”

Previous Work on 76015

Blanford et al, 1974; Wentworth et al, 1999:

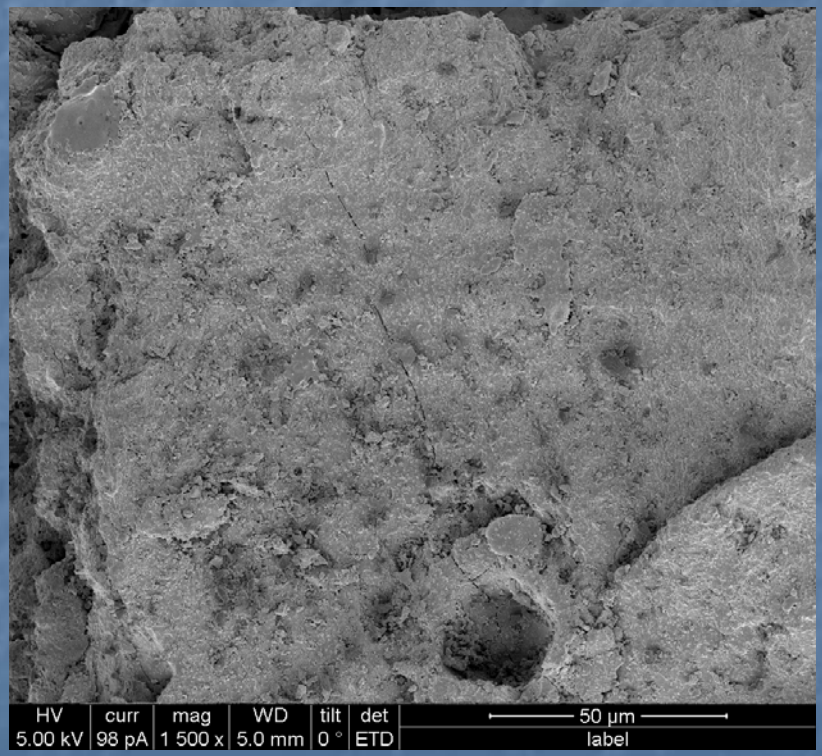


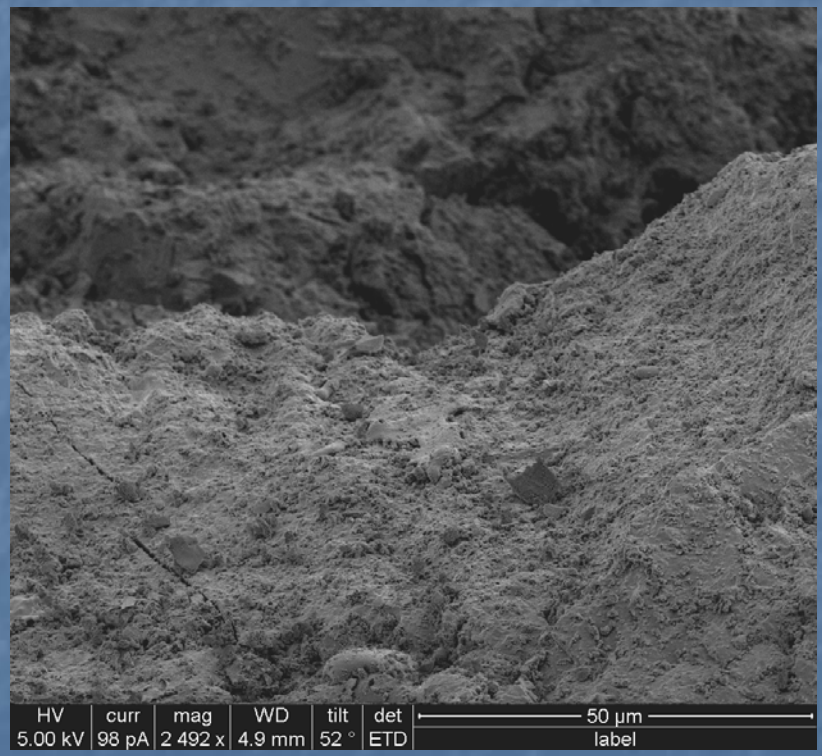
- SEM – surfaces only
- TEM – microtomed samples

FIB - Focused Ion Beam

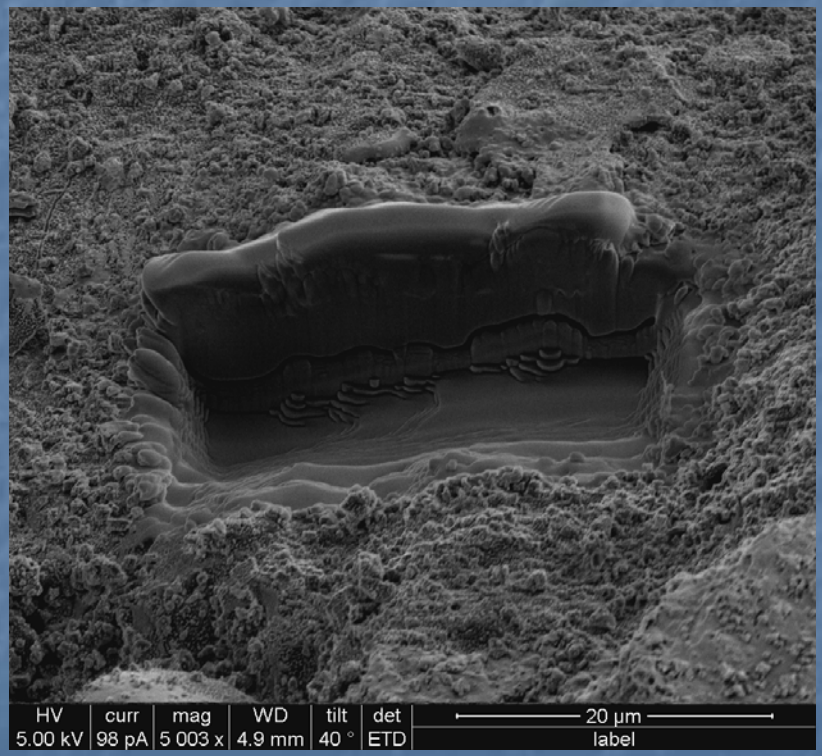
- Uses gallium ions to “cut” material
- Produces a cross section through the weathered zone
- Allows us to examine the depths and structures of the weathered coatings in place

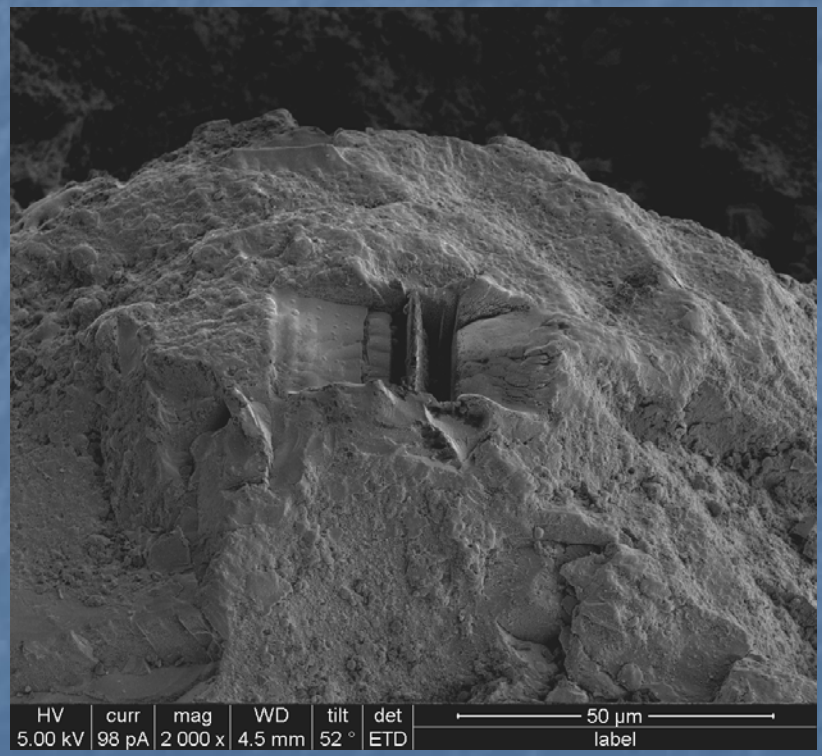
FIB technique



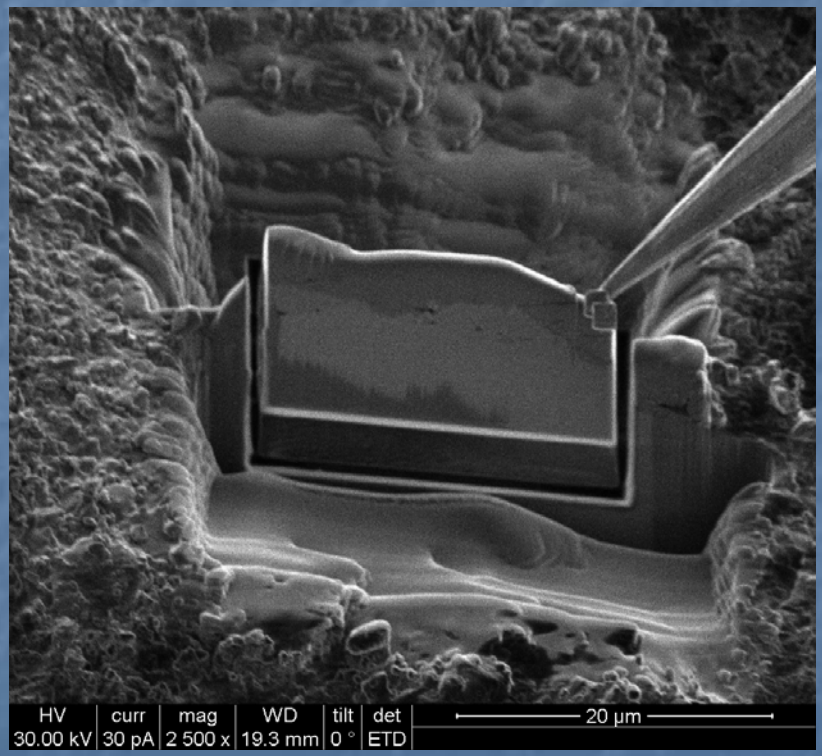


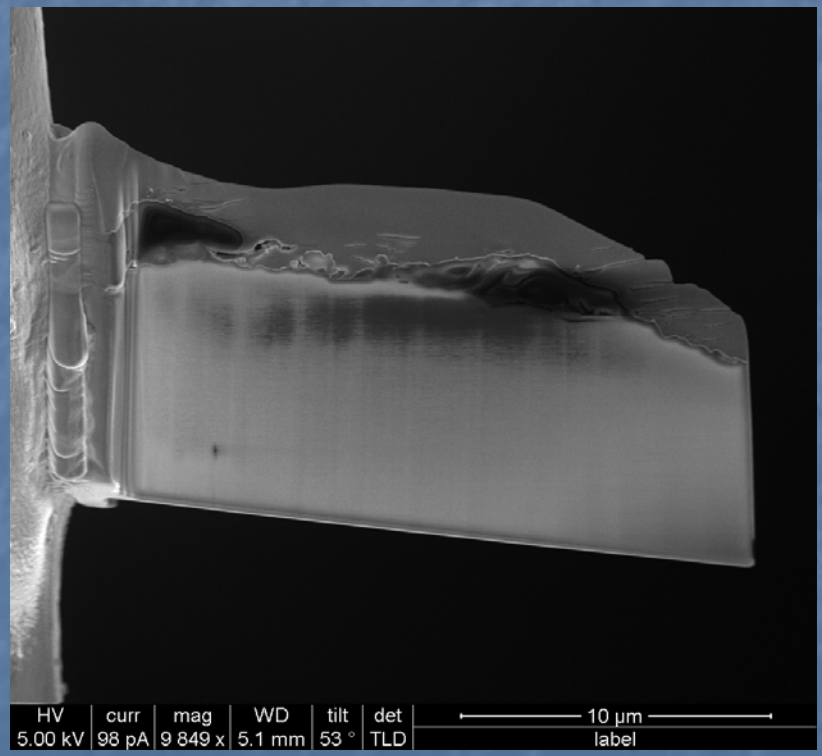
FIB technique



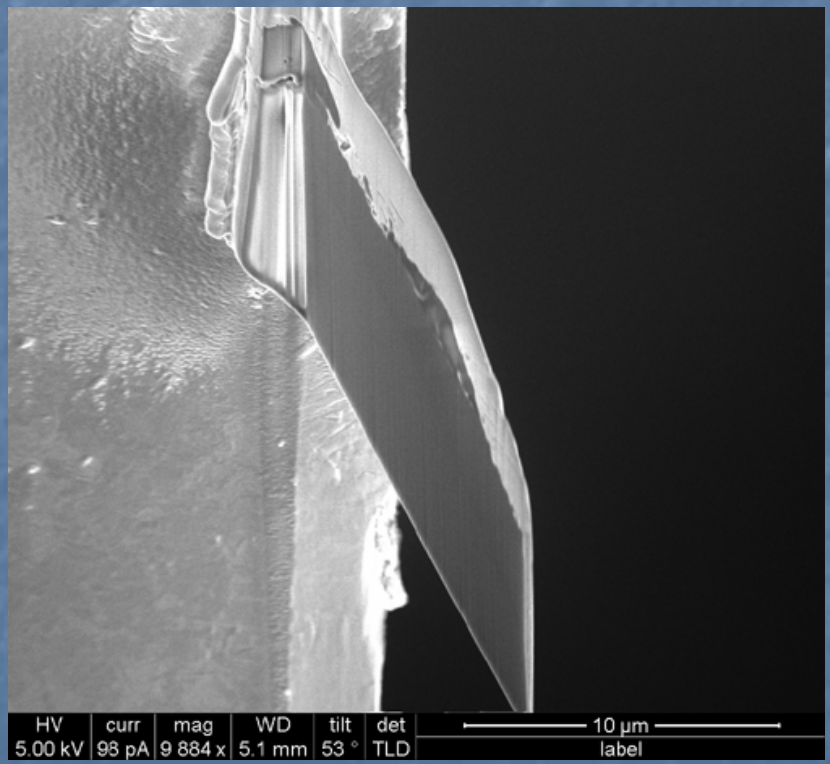


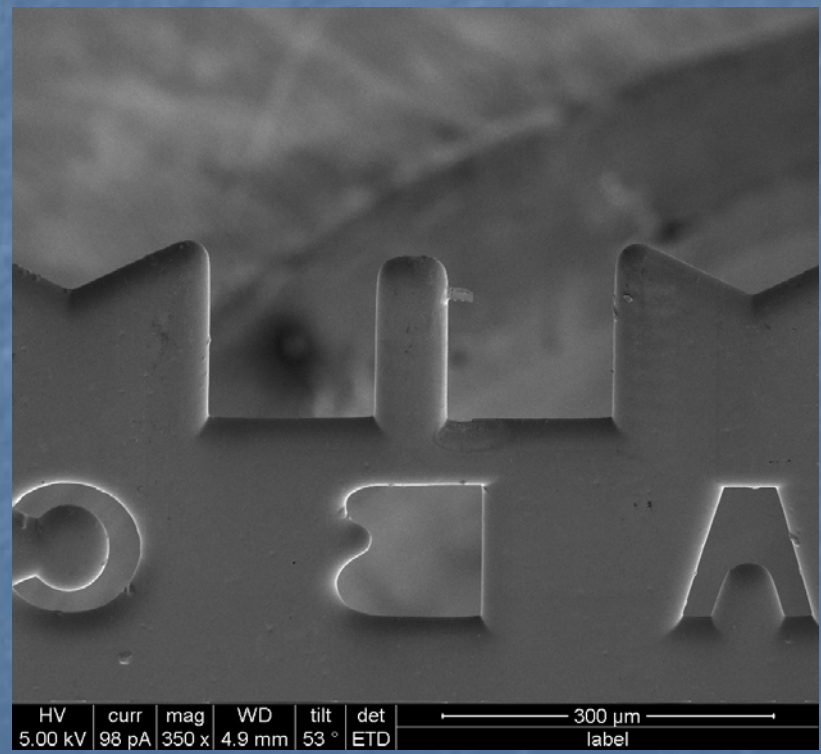
FIB technique



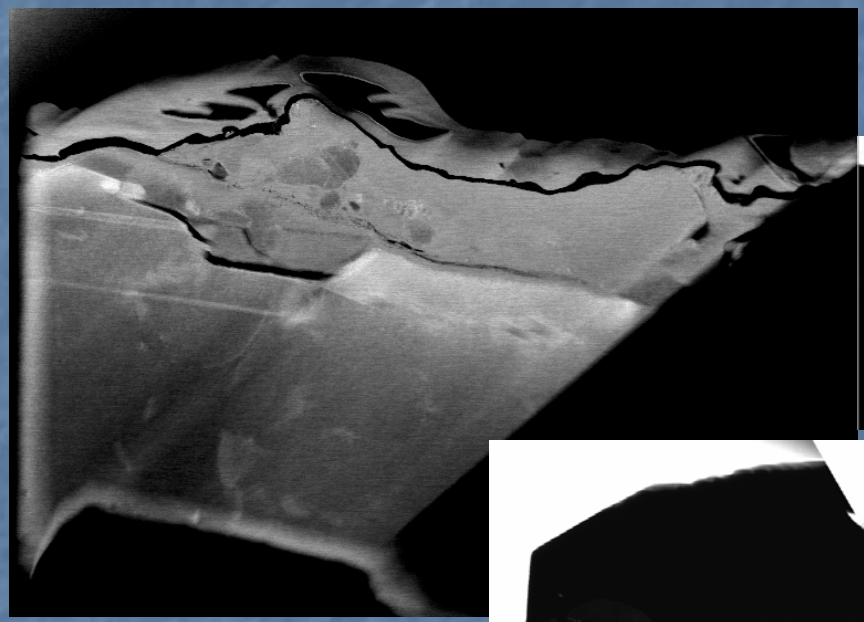


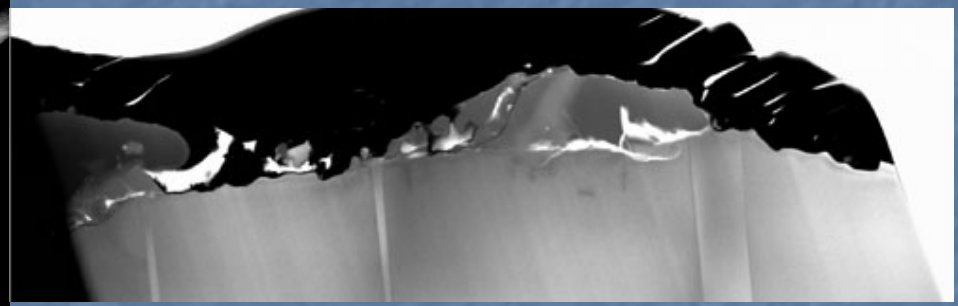
FIB technique



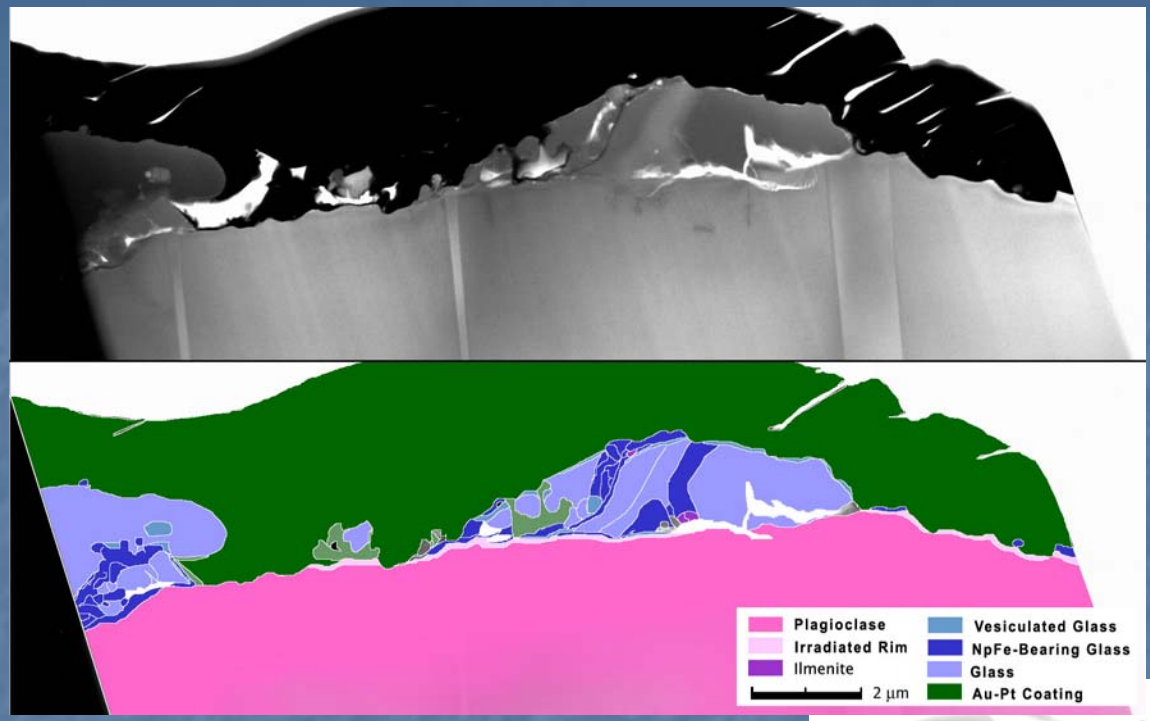


3 Focused Ion Beam samples

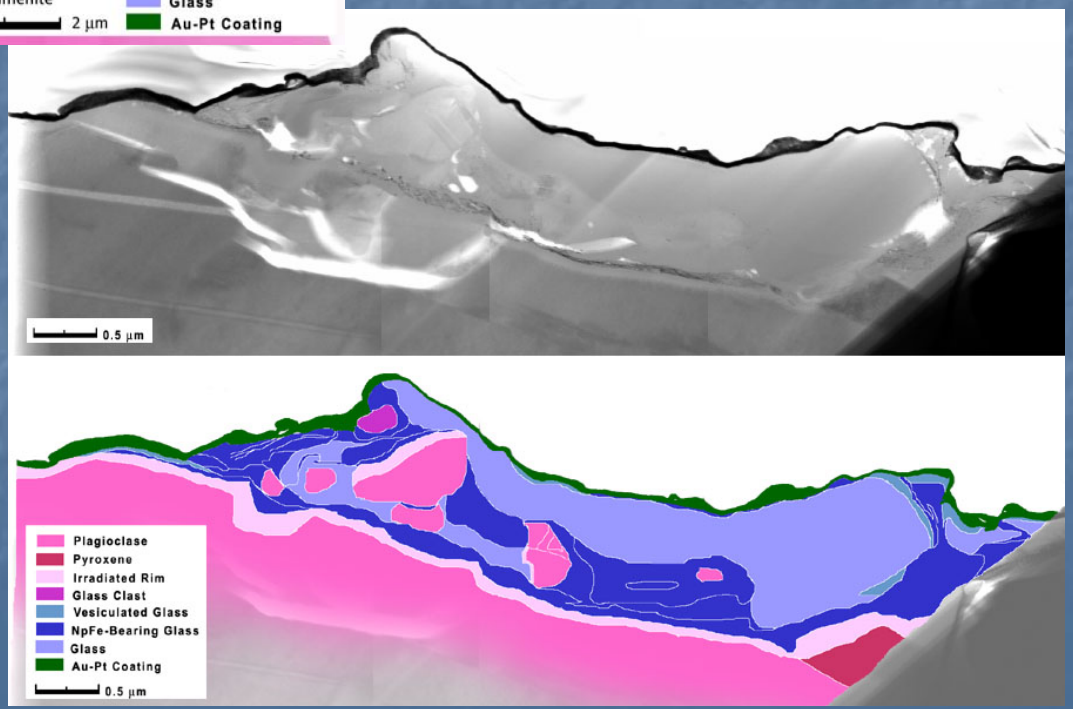




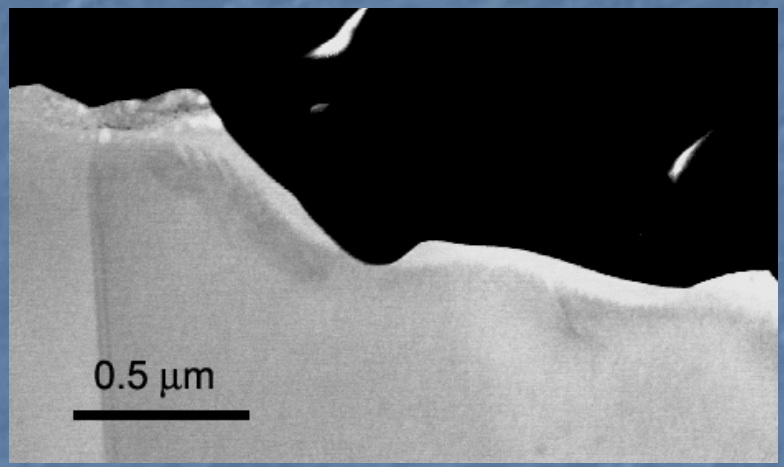
Common weathering components

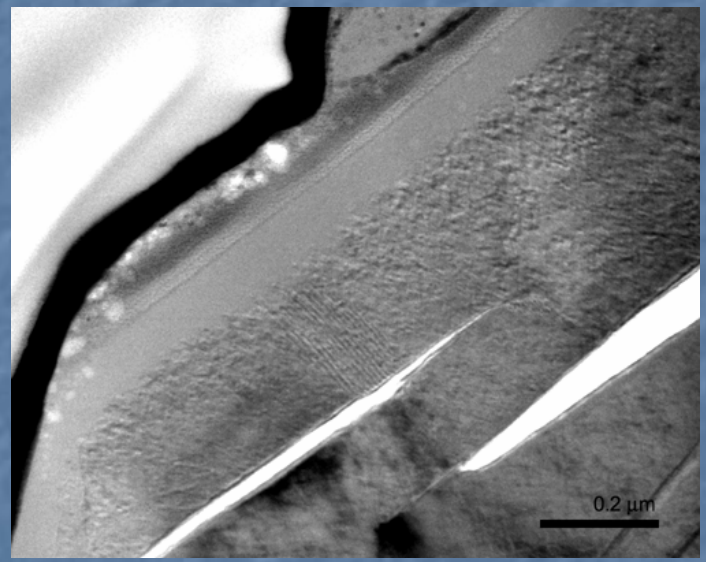


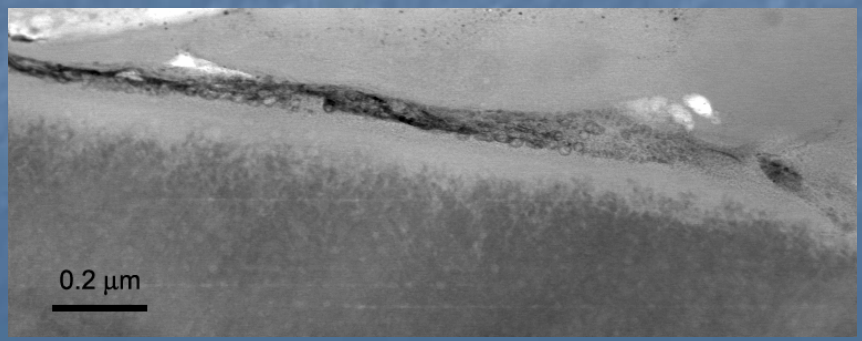
- Irradiated rim
- Tracks
- Layers of glass
- Embedded grains
- Vapor deposits
- Vesiculated rims

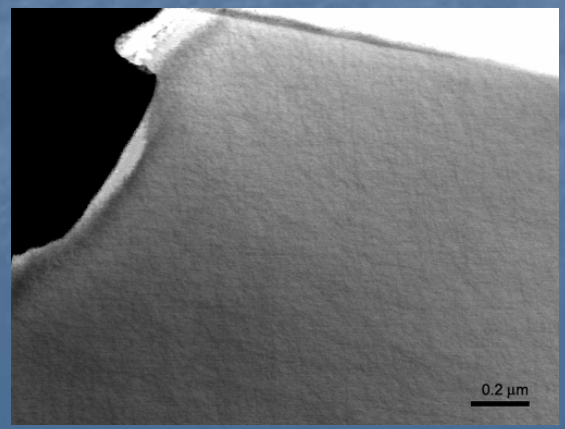


Irradiated Rim / Tracks

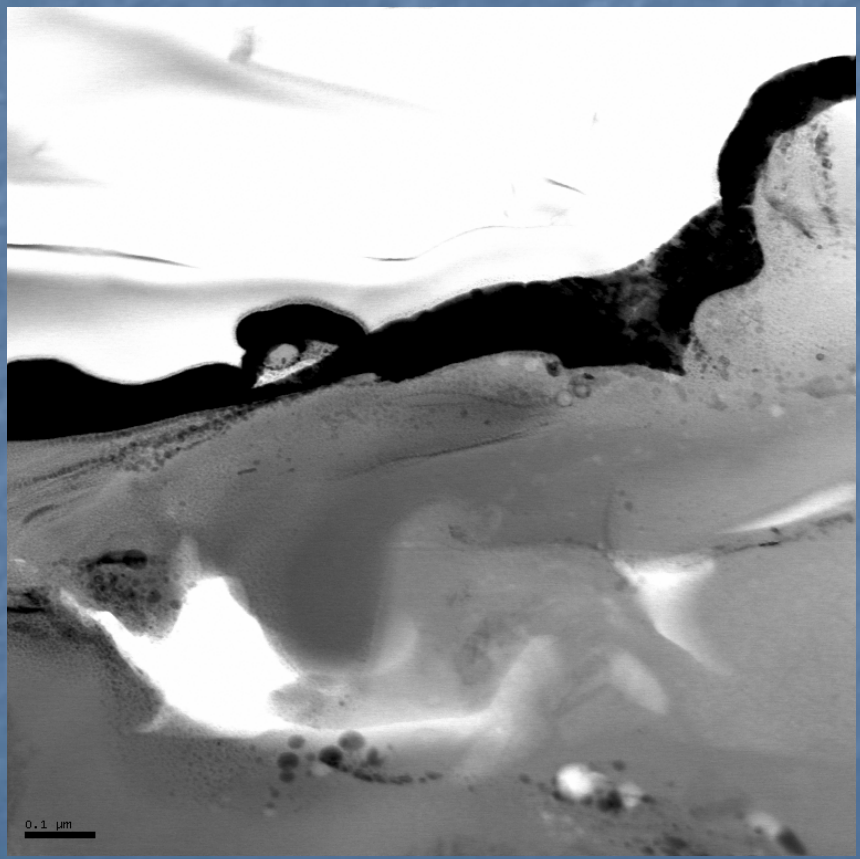


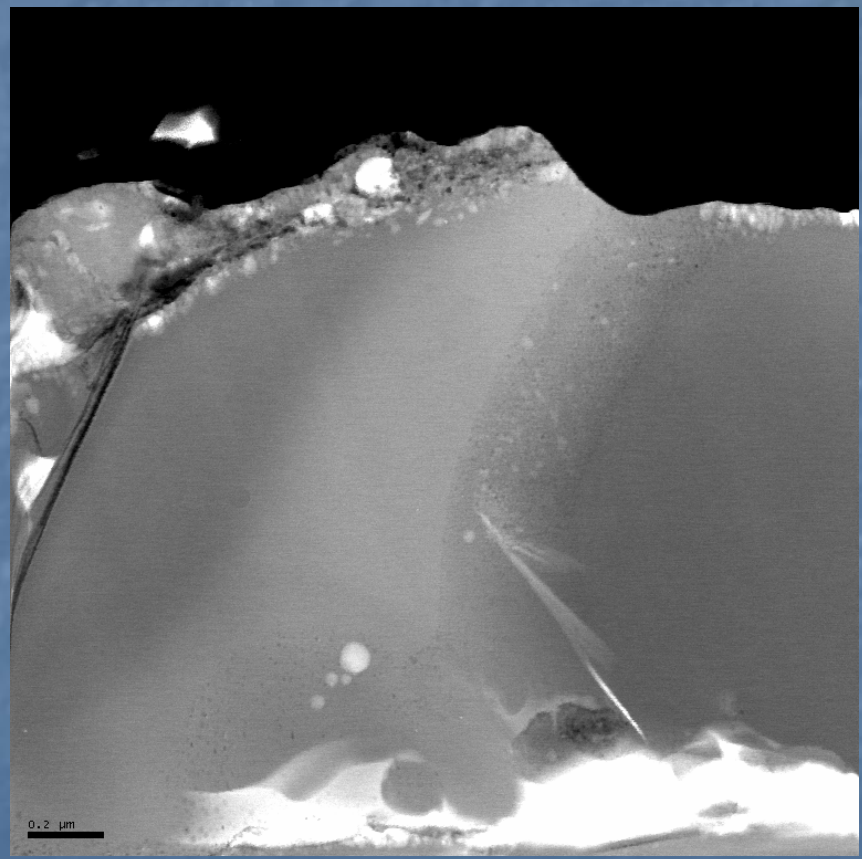




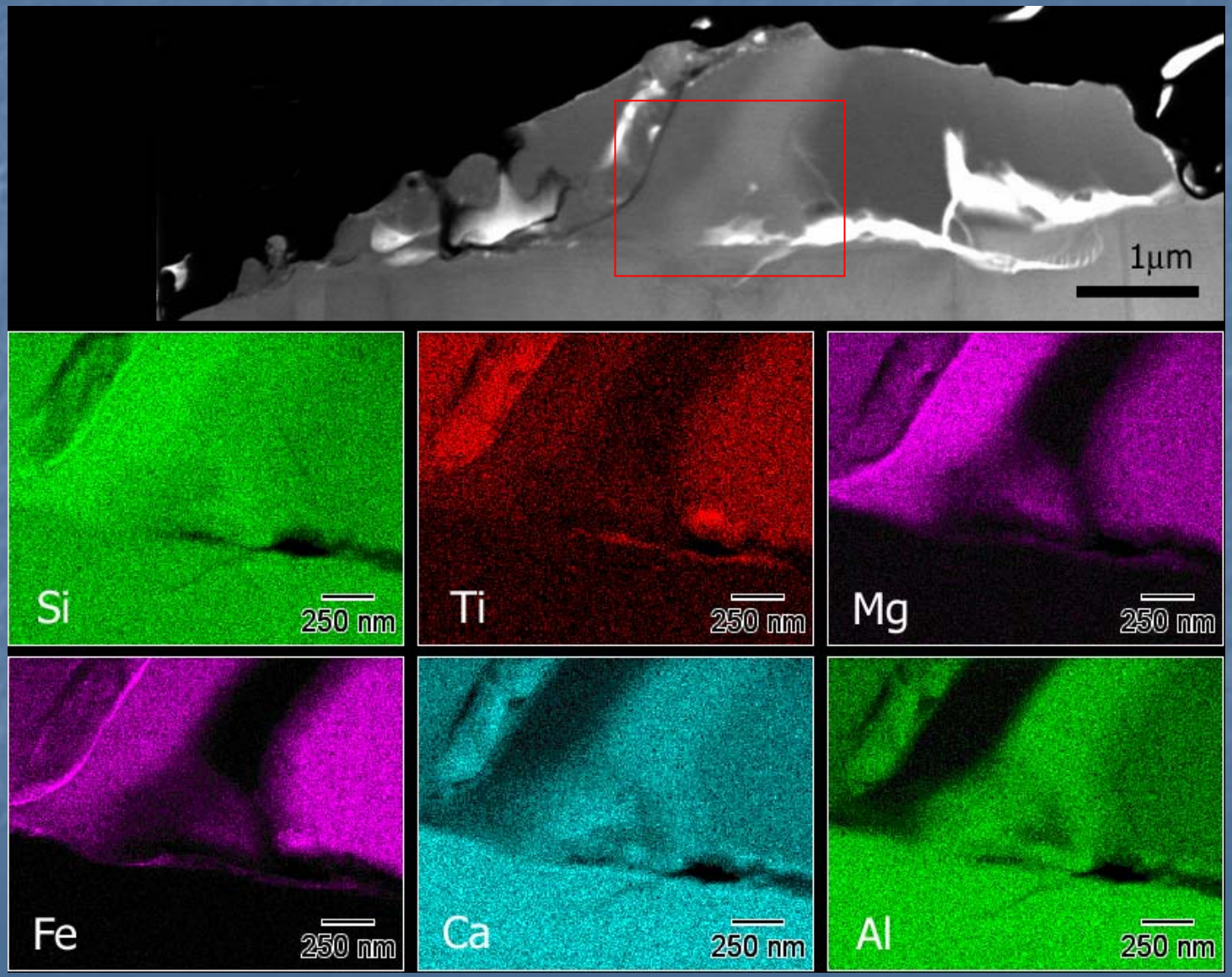


Layers of Glass

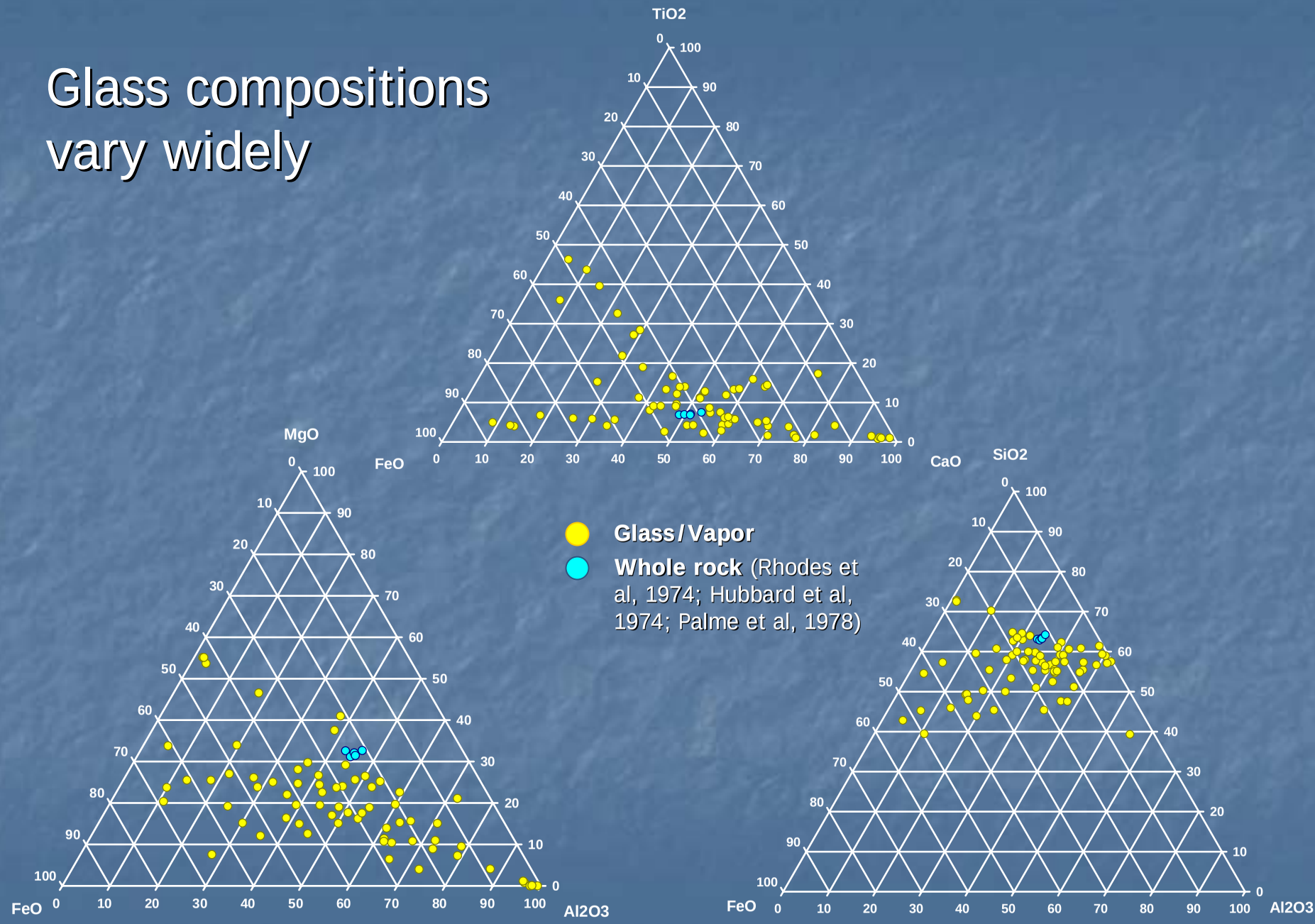




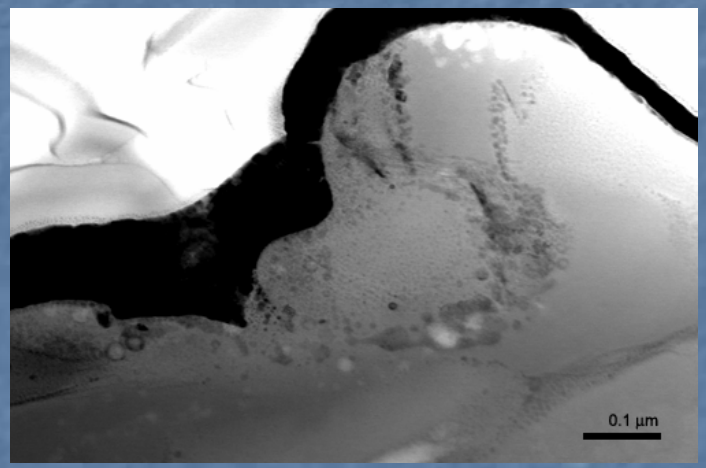
Layers of Glass

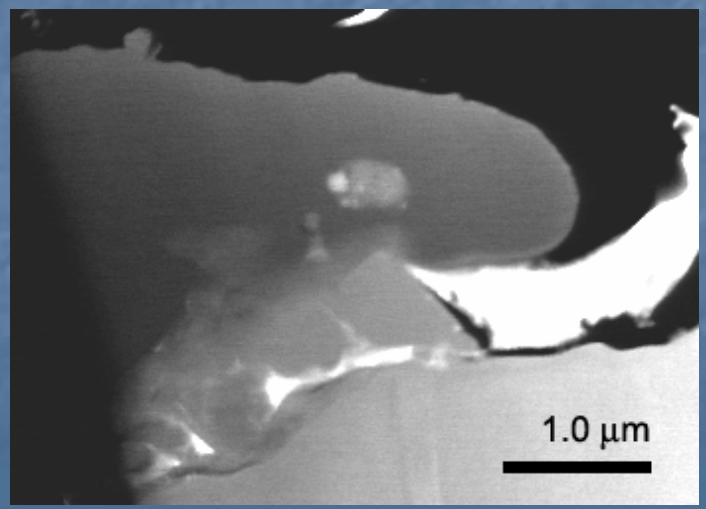


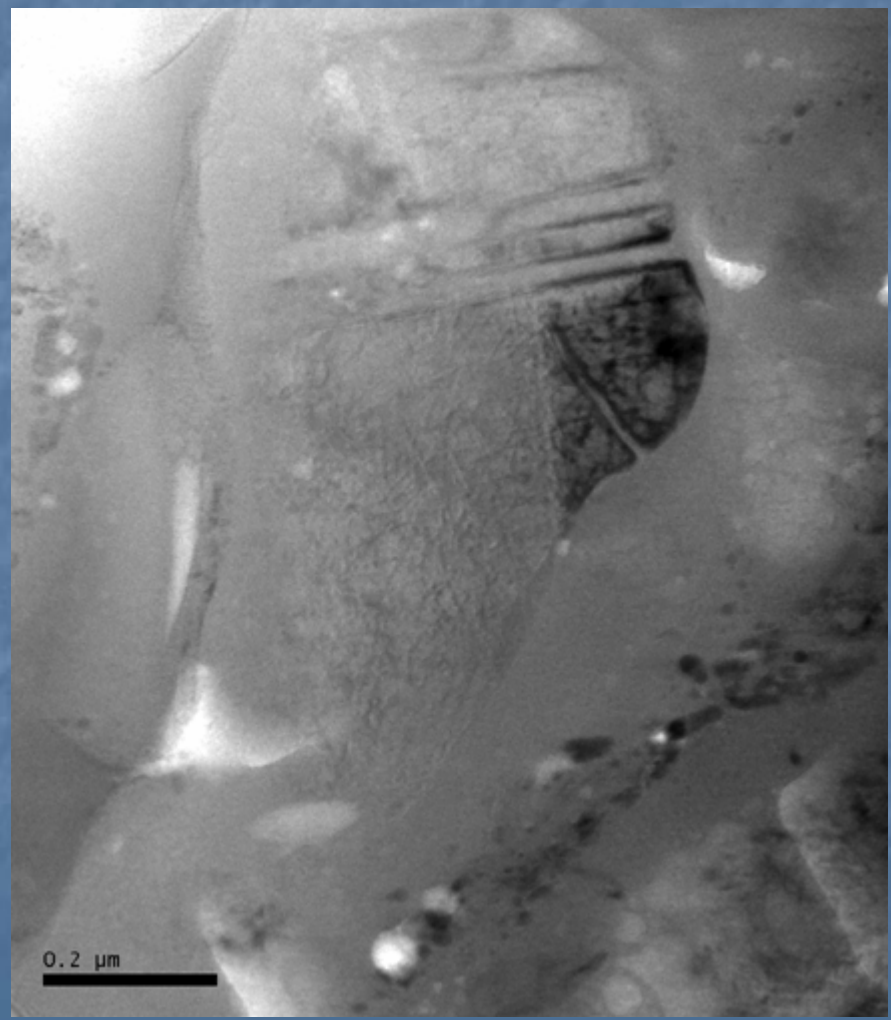
Glass compositions vary widely



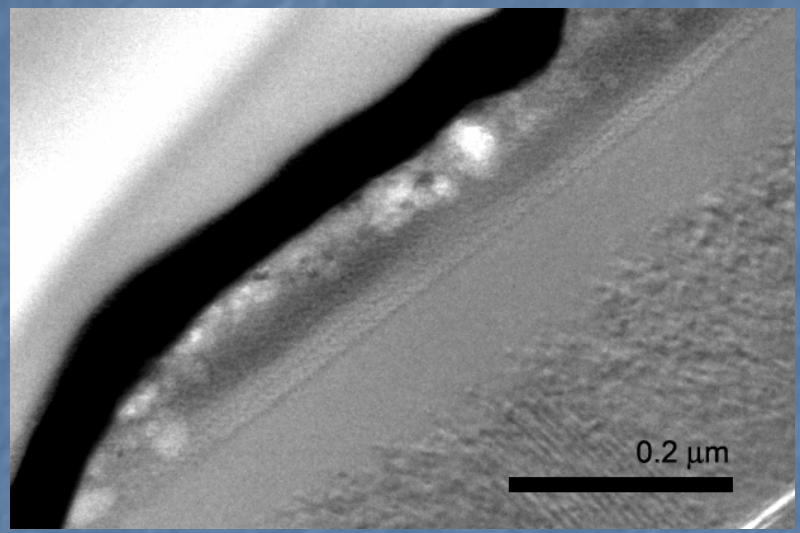
Embedded Grains

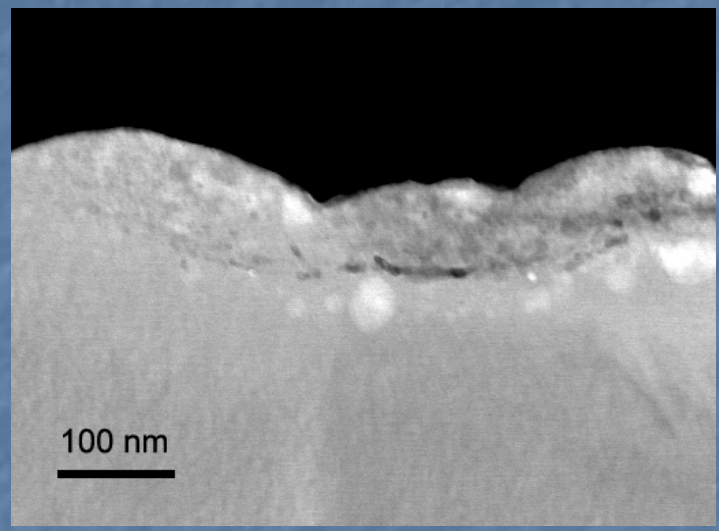


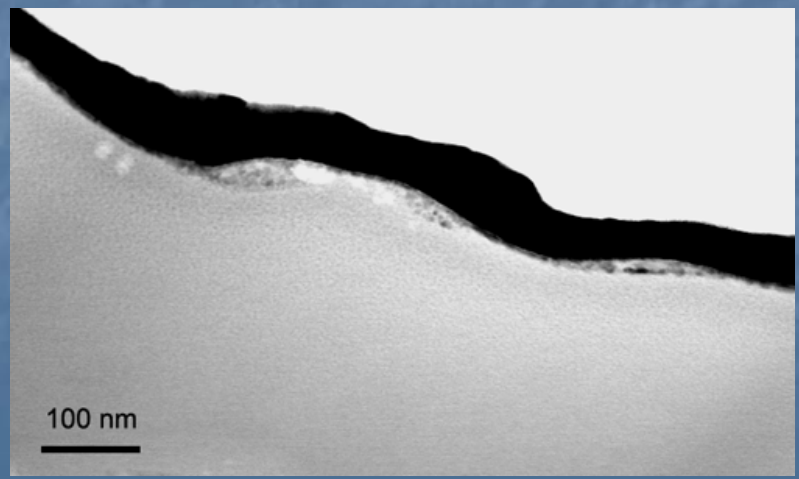




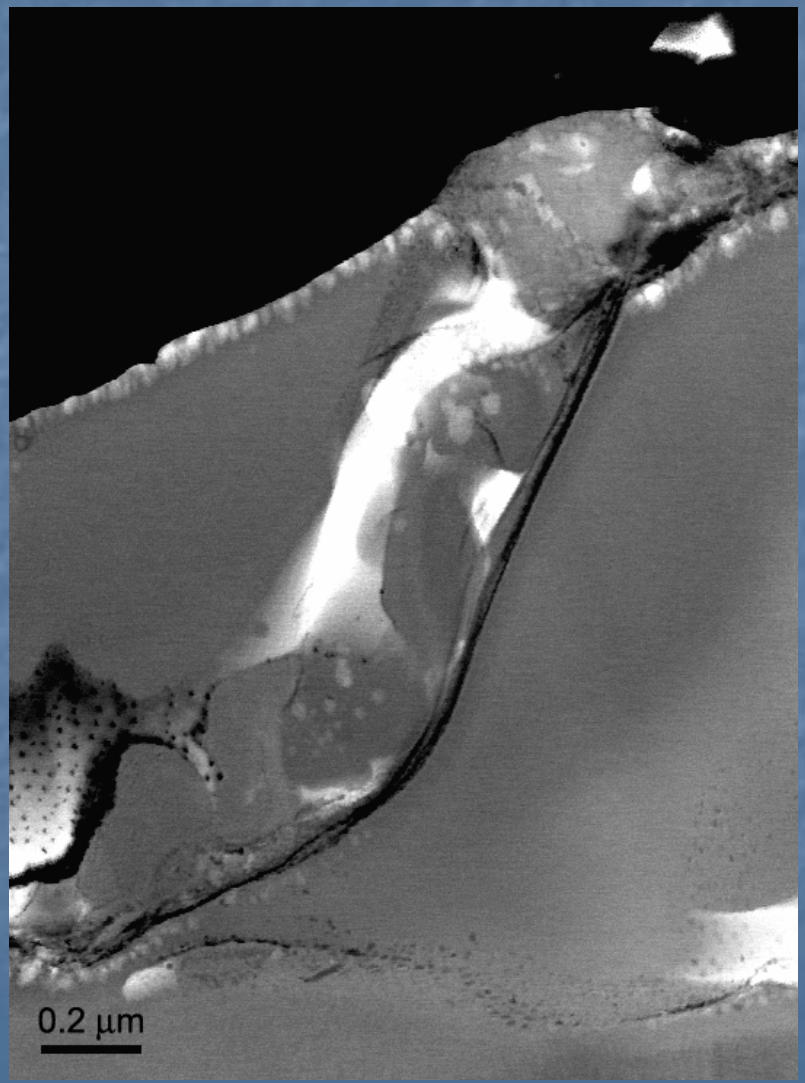
Vapor Deposits

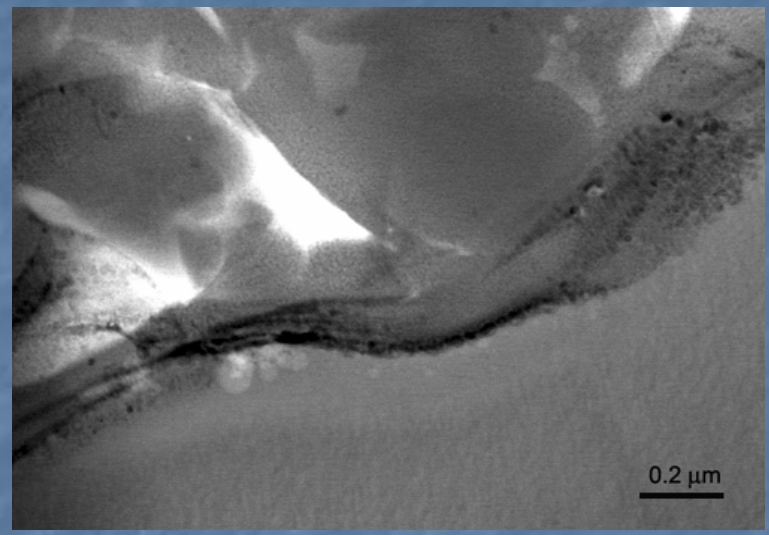


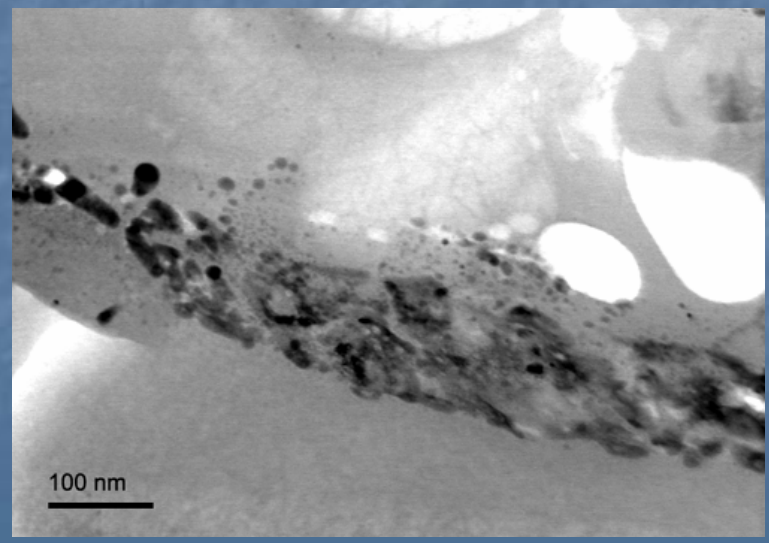




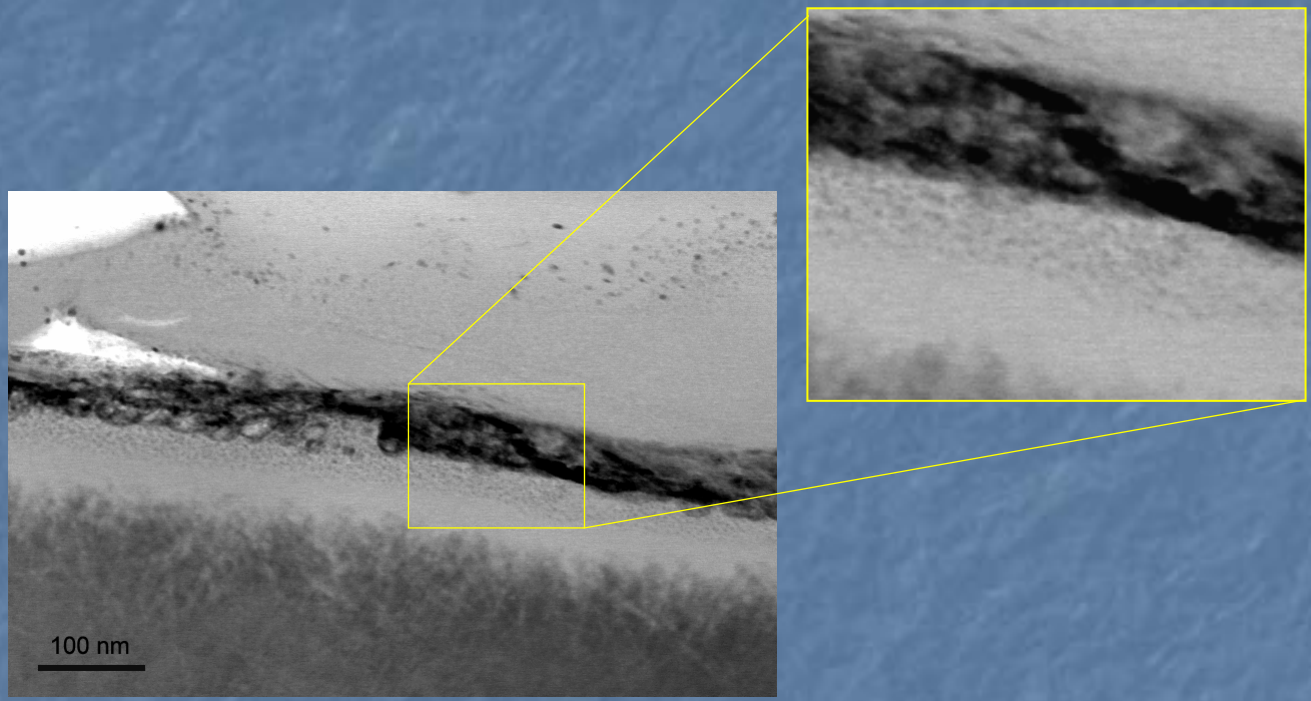
Vapor Deposits

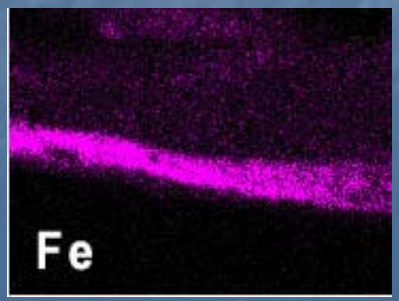


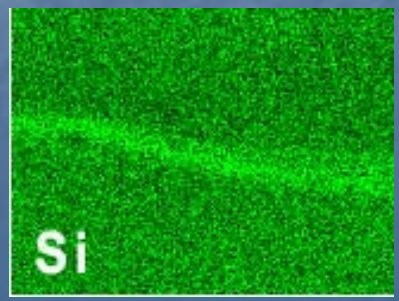


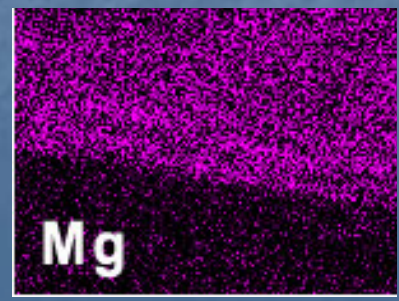


Vapor Deposits

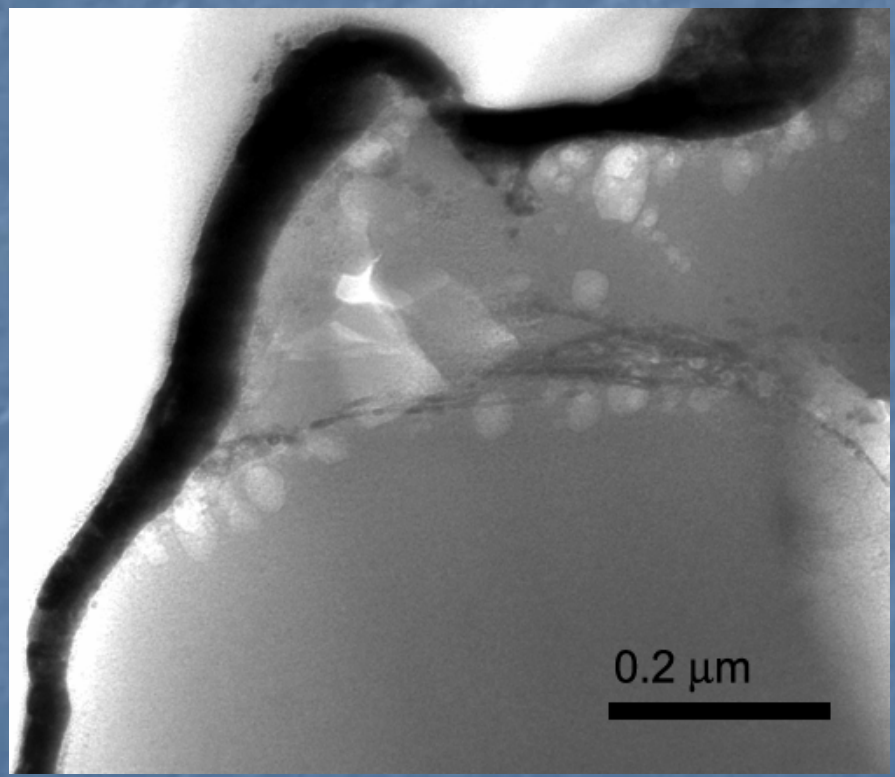


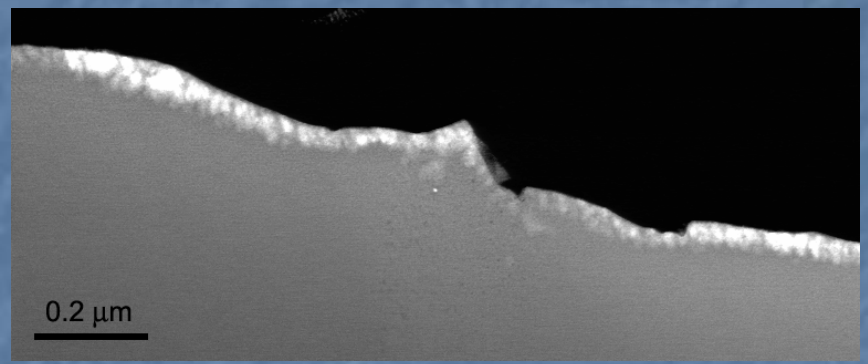


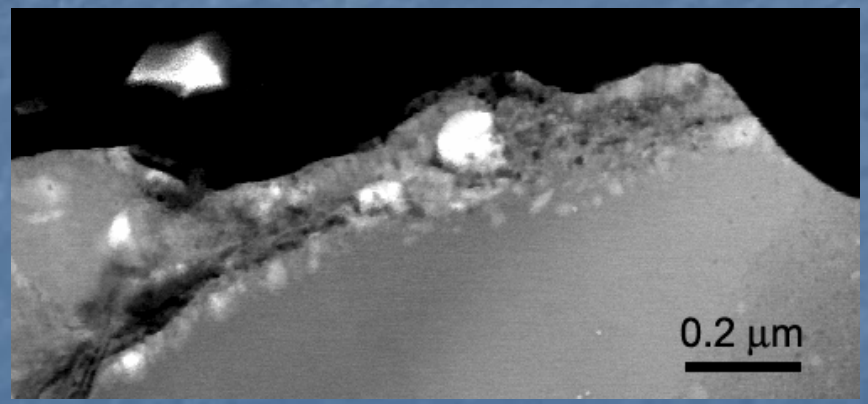




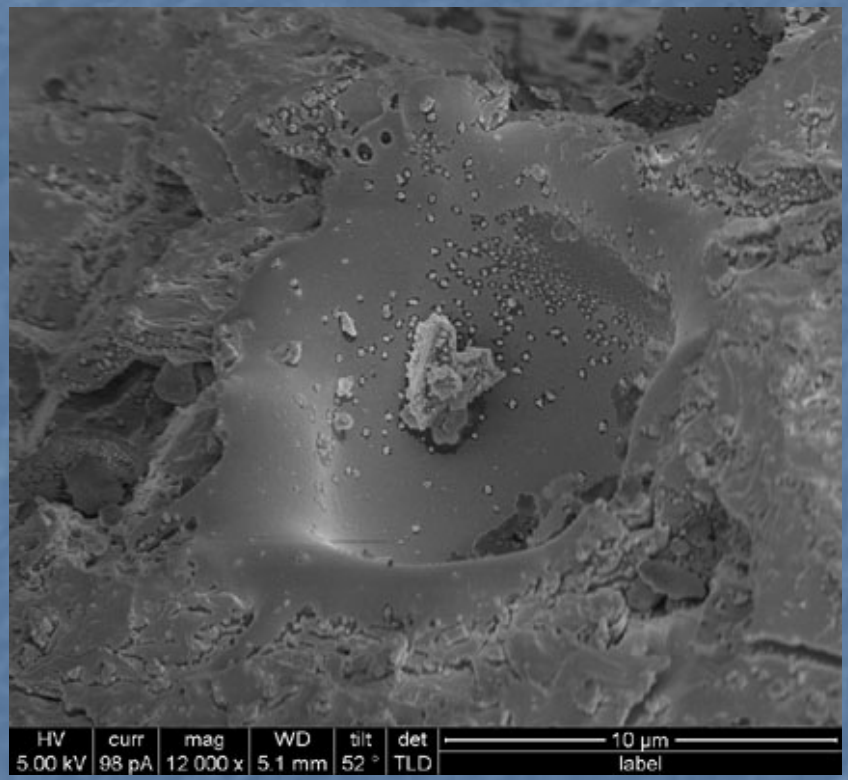
Vesiculated Rims

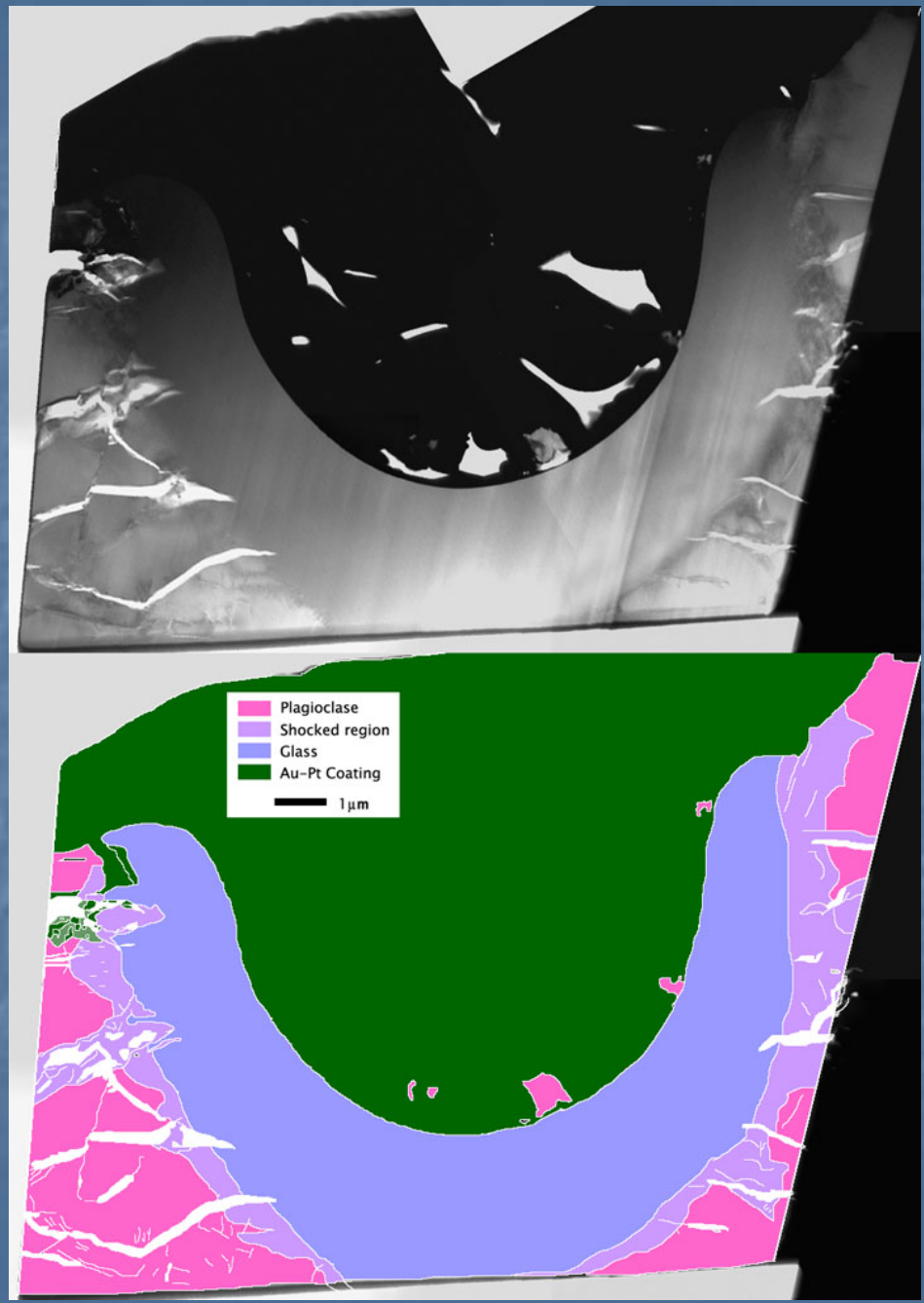




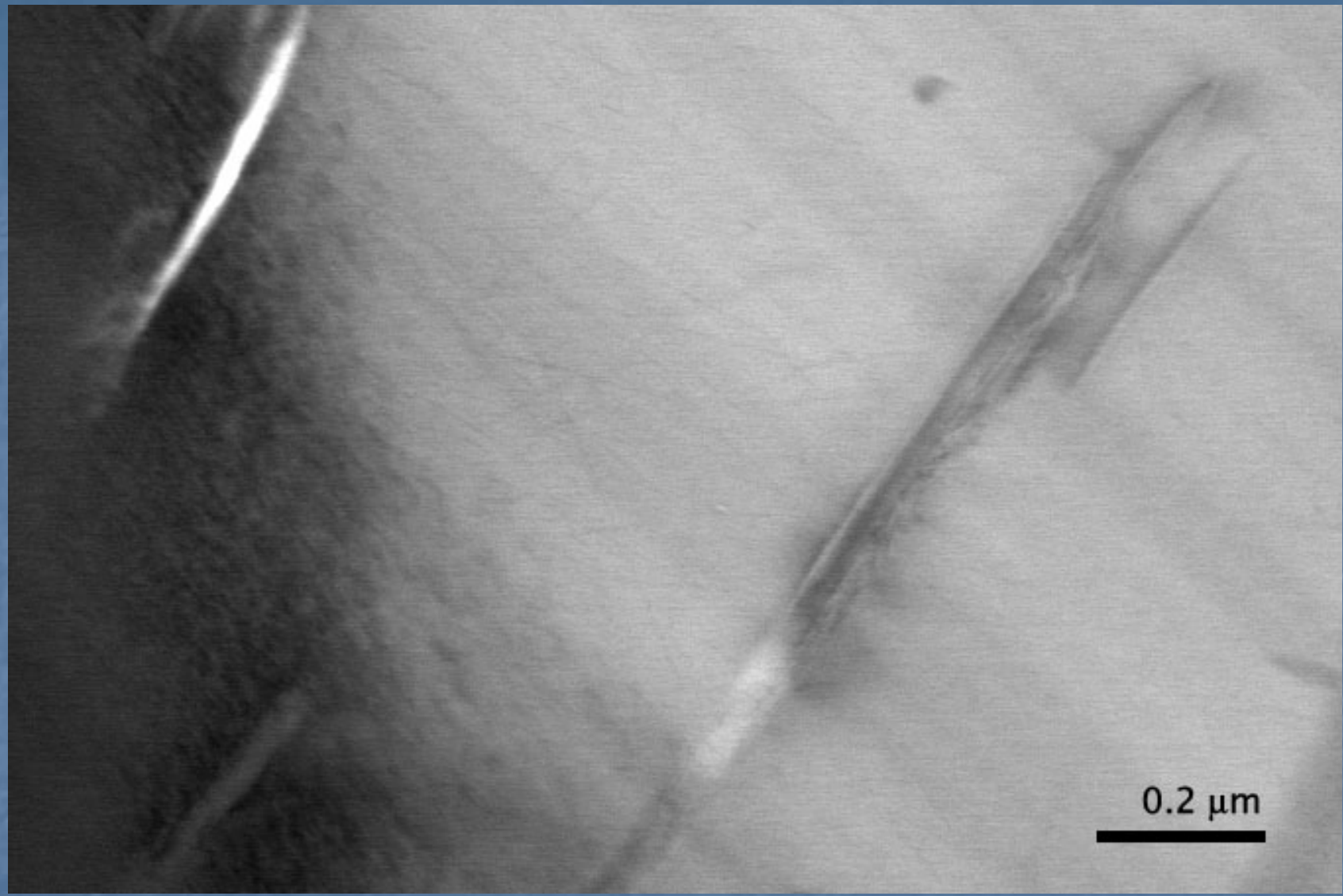


Microcrater cross-section





“feathery” texture at interface between melt liner and grain



Tracks extend right up to interface, suggesting minimal heating, as tracks are annealed around 650-850°C (Fraundorf et al, 1980; Sandford and Bradley, 1989)

Summary

- The Focused Ion Beam (FIB) technique has allowed us a unique view into 76015
- The surface of this rock records a long history of space weathering events.
- More samples will help constrain which processes are most common and what events are more rare.
- By volume, there is considerably more melt deposited than vapor.
- Impact and melt deposition on this scale is not strong enough to anneal tracks in adjacent material.